

How large can the branching ratio of $B_s \rightarrow \tau^+\tau^-$ be ?

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Motivated by the large like-sign dimuon charge asymmetry observed recently, whose explanation would require an enhanced decay rate of $B_s \rightarrow \tau^+\tau^-$, we explore how large a branching ratio of this decay mode is allowed by the present constraints. We use bounds from the lifetimes of B_d and B_s , constraints from the branching ratios of related $b \rightarrow s\tau^+\tau^-$ modes, as well as measurements of the mass difference, width difference and CP-violating phase in the B_s - \bar{B}_s system. Using an effective field theory approach, we show that a branching ratio as high as 15% may be allowed while being consistent with the above constraints. The measurement of this decay, therefore, may be within the reach of current experiments, and can point toward a specific class of new physics models. We also explore the possible enhancement of this decay in models with leptoquarks and Z' , and find that in the latter case the branching ratio may be as much as 5%, which can alleviate the dimuon anomaly to some extent.

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I. INTRODUCTION

In 2010, the DØ Collaboration reported an anomalously large CP-violating like-sign dimuon charge asymmetry in the B system [1, 2], which was strengthened by the updated measurement [3]. The weighted average with the older CDF results [4] gives

$$A_{\text{SL}}^b = -(74.1 \pm 19.3) \times 10^{-4}, \quad (1)$$

which is a 3.8σ deviation from the Standard Model (SM) prediction $A_{\text{SL}}^{b \text{ SM}} = -(2.3 \pm 0.4) \times 10^{-4}$ [5].

The measured dimuon charge asymmetry is a linear combination of the semileptonic asymmetries a_{SL}^d and a_{SL}^s in the B_d and B_s sectors, respectively. Therefore, the new physics (NP) may contribute through either of these two sectors. However, since

$$a_{\text{SL}}^q = \frac{\Delta\Gamma_q}{\Delta m_q} \tan \phi_q^{\text{SL}} \quad (q = d, s), \quad (2)$$

where $\Delta\Gamma_q$ is the width difference in the B_q - \bar{B}_q system and ϕ_q^{SL} is the CP-violating phase in the semileptonic decays, an enhancement in a_{SL}^q is necessarily accompanied by an enhancement in $\tan \phi_q^{\text{SL}}$ and/or in $\Delta\Gamma_q$. In the B_d sector, since $\tan \phi_d^{\text{SL}} \approx 0.075$ in the SM already, a further large enhancement would amount to fine-tuning. Also, an enhancement in $\Delta\Gamma_d$ would imply the NP contribution of a few percent to the branching ratios of decay modes common to B_d and \bar{B}_d , which is ruled out by the measurements of such modes [6]. In the B_s sector on the other hand, $\phi_s^{\text{SL}} \approx 0.004$ in the SM [5], and the branching ratios of some of the decay modes, notably of $B_s \rightarrow \tau^+\tau^-$, have not yet been strongly constrained. Therefore NP that contributes to $B_s \rightarrow \tau^+\tau^-$ would be a prime candidate to account for the dilepton anomaly [7].

Indeed, it has been shown that the only effective four-Fermi operators that can account for such an enhanced A_{SL}^b are $(\bar{b}\Gamma s)(\bar{\tau}\Gamma\tau)$ and $(\bar{b}\Gamma s)(\bar{c}\Gamma c)$ [8]. We, therefore, investigate how large the branching ratio $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ can be.

Since the desired NP is expected to contribute to B_s and B_d decays to different extents, it may lead to a difference in the lifetimes of B_d and B_s , which is otherwise expected to be $\lesssim 1\%$ in the SM [5]. The recent LHCb measurements [9] yield $\tau_{B_s}/\tau_{B_d} = 1.002 \pm 0.014 \pm 0.012$. This indicates that at the 2σ level, the branching ratio $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ up to 3.5% is still allowed, even if there is no NP contribution to B_d decays. If NP contributes to B_d decays, this bound will be further relaxed. Note that this would be a large enhancement: the value of this branching ratio in the SM is $\approx 7 \times 10^{-7}$ [10].

Measurements from other modes of the form $b \rightarrow s\tau^+\tau^-$, like $B_d \rightarrow X_s\tau^+\tau^-$, $B_d \rightarrow K\tau^+\tau^-$ and $B_d \rightarrow K^*\tau^+\tau^-$, can restrict the NP contribution to $B_s \rightarrow \tau^+\tau^-$ since they involve the same effective four-Fermi operator. However the experimental information on such decay modes is very poor. The only direct bound available at present is the 90% BaBar limit of [11]

$$\mathcal{B}(B^+ \rightarrow K^+\tau^+\tau^-)|_{q^2 > 14.23 \text{ GeV}^2} < 0.33\%. \quad (3)$$

It was suggested in [10] that a dedicated experimental analysis of the LEP data using the missing energy spectrum as in [12] could be used to constrain $\mathcal{B}(B_d \rightarrow X_s\tau^+\tau^-)$ and $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ to 5%; however such an analysis has not been performed to our knowledge. The bound on $\mathcal{B}(B_d \rightarrow X_s\tau^+\tau^-)$ obtained in [13] also weakens considerably when the theoretical uncertainties in $\mathcal{B}(B \rightarrow K\ell\nu + \text{anything})$ are taken into account. The charm counting in B_d decays yields $\mathcal{B}(B_d \rightarrow \text{no charm}) \leq 14\%$ at 2σ [13]. This would give $\mathcal{B}(B_d \rightarrow X_s\tau^+\tau^-) \lesssim 12.5\%$, by subtracting the SM contribution of 1.5% to charmless B decays [14]. The compatibility between these bounds and a large $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ needs to be investigated in a model-independent framework as well as in the context of spe-

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cific models, which we shall do in this paper.

The models with scalar leptoquarks [7, 10, 15] and with flavor-dependent Z' couplings [16–18] have been proposed in the literature in order to enhance the $b \rightarrow s\tau^+\tau^-$ decay rates, to account for the dimuon anomaly as well as the measurements of width difference in the B_s - \bar{B}_s system and the CP-violating phase $B_s \rightarrow J/\psi\phi$. We explore the two models above to check whether they are still able to account for all the data, at the same time allowing for an enhanced dimuon asymmetry.

II. MODEL-INDEPENDENT ANALYSIS: HAMILTONIAN FOR B_s - \bar{B}_s MIXING

The NP that contributes to the decay modes $b \rightarrow s\tau^+\tau^-$ directly influences B_s - \bar{B}_s mixing, by contributing to the dispersive (M_{12}^s) as well as absorptive (Γ_{12}^s) part of the effective Hamiltonian for this mixing. These contributions may result in an enhanced value of the lifetime difference $\Delta\Gamma_s$ and the CP-violating phase $\phi_s^{\text{SL}} = \text{Arg}[-M_{12}^s/\Gamma_{12}^s]$ and, hence, will be restricted by the recent measurements of $B_s \rightarrow J/\psi\phi$ at the LHCb [19]. In this section, we shall explore what the data have to say about the NP contributions to M_{12}^s and Γ_{12}^s .

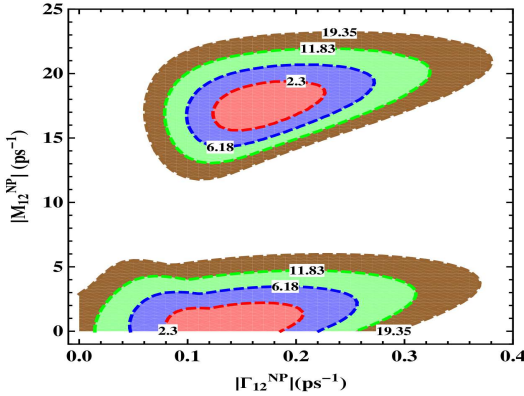


FIG. 1. The goodness-of-fit contours in the $|M_{12}^{\text{NP}}|$ - $|\Gamma_{12}^{\text{NP}}|$ plane, where the phases of M_{12}^{NP} and Γ_{12}^{NP} are varied over. The red, blue, green and brown regions have χ^2 values less than 2.3, 6.18, 11.83, and 19.35, respectively, corresponding to regions allowed at 1σ , 2σ , 3σ , and 4σ , respectively. The same convention is followed in all figures.

We follow the recent analysis [20], with the inclusion of newly available data. We parameterize the NP by

$$M_{12}^s = M_{12}^{\text{SM}} + M_{12}^{\text{NP}}, \quad \Gamma_{12}^s = \Gamma_{12}^{\text{SM}} + \Gamma_{12}^{\text{NP}}, \quad (4)$$

where we take the central values of M_{12}^{SM} and Γ_{12}^{SM} to be $M_{12}^{\text{SM}} = 8.65 e^{(\pi-0.04)i} \text{ ps}^{-1}$ and $\Gamma_{12}^{\text{SM}} = 0.0435 e^{-0.04i} \text{ ps}^{-1}$. We investigate constraints on the two complex quantities (four parameters) M_{12}^{NP} and Γ_{12}^{NP} from the measured values of Δm_s , $\Delta\Gamma_s$, A_{SL}^b and the CP-violating phase in the $B_s \rightarrow J/\psi\phi$ decay ($\phi_s^{J/\psi\phi}$). The results of the χ^2 fit projected in the $(|M_{12}^{\text{NP}}|, |\Gamma_{12}^{\text{NP}}|)$ plane are shown

in Fig. 1. We assume all the measurements to be independent for simplicity, add the theoretical and experimental errors in quadrature, and vary over the phases of the two quantities M_{12}^{NP} and Γ_{12}^{NP} .

The origin in this figure is the SM, which has $\chi^2 \simeq 15$. This dramatically quantifies the failure of the SM to accommodate all the current data. There are two regions in the parameter space that are consistent with the current data, one of which is also consistent with $M_{12}^{\text{NP}} = 0$, i.e. there is no need for NP to contribute to the dispersive part of the Hamiltonian. On the other hand, consistency with the data even to 3σ (i.e. $\chi^2 < 11.83$) seems to require a nonzero NP contribution Γ_{12}^{NP} .

The 2σ preferred range of $|\Gamma_{12}^{\text{NP}}|$ is $(0.05, 0.25) \text{ ps}^{-1}$. Even the lower end of this range yields $\mathcal{B}(B_s \rightarrow \tau^+\tau^-) \approx 15\%$ if Γ_{12}^{NP} is coming entirely from $B_s \rightarrow \tau^+\tau^-$. Thus, the model-independent constraints from B_s - \bar{B}_s mixing on $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ are rather weak and easily allow values as large as $\sim 15\%$.

III. MODEL INDEPENDENT ANALYSIS: HAMILTONIAN FOR $b \rightarrow s\tau^+\tau^-$ DECAY

Within the SM, the effective Hamiltonian for the quark-level transition $b \rightarrow s\tau^+\tau^-$ is

$$\mathcal{H}_{\text{eff}}^{\text{SM}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \times \quad (5)$$

$$\left\{ \sum_{i=1}^6 C_i(\mu) \mathcal{O}_i(\mu) + C_7 \frac{e}{16\pi^2} m_b (\bar{s} \sigma_{\mu\nu} P_R b) F^{\mu\nu} + C_9 \frac{\alpha_{em}}{4\pi} (\bar{s} \gamma^\mu P_L b) \bar{\tau} \gamma_\mu \tau + C_{10} \frac{\alpha_{em}}{4\pi} (\bar{s} \gamma^\mu P_L b) \bar{\tau} \gamma_\mu \gamma_5 \tau \right\},$$

where $P_{L,R} = (1 \mp \gamma_5)/2$. The operators \mathcal{O}_i ($i = 1, \dots, 6$) correspond to the P_i of Ref. [21], and $m_b = m_b(\mu)$ is the running b -quark mass in the $\overline{\text{MS}}$ scheme. We use the SM Wilson coefficients as given in Ref. [22].

We now parameterize NP through the addition of new operators with distinct Lorentz structures to the effective Hamiltonian for $b \rightarrow s\tau^+\tau^-$. We consider only scalar-pseudoscalar and vector-axial vector operators and exclude tensor ones. The new effective Hamiltonian is

$$\mathcal{H}_{\text{eff}}(b \rightarrow s\tau^+\tau^-) = \mathcal{H}_{\text{eff}}^{\text{SM}} + \mathcal{H}_{\text{eff}}^{\text{VA}} + \mathcal{H}_{\text{eff}}^{\text{SP}}, \quad (6)$$

where the new operators are

$$\begin{aligned} \mathcal{H}_{\text{eff}}^{\text{VA}} &= -\frac{g_{\text{NP}}^2}{\Lambda^2} [C_V (\bar{s} \gamma^\mu P_L b) + C'_V (\bar{s} \gamma^\mu P_R b)] (\bar{\tau} \gamma_\mu \tau) \\ &\quad -\frac{g_{\text{NP}}^2}{\Lambda^2} [C_A (\bar{s} \gamma^\mu P_L b) + C'_A (\bar{s} \gamma^\mu P_R b)] (\bar{\tau} \gamma_\mu \gamma_5 \tau), \\ \mathcal{H}_{\text{eff}}^{\text{SP}} &= -\frac{g_{\text{NP}}^2}{\Lambda^2} [C_S (\bar{s} P_R b) + C'_S (\bar{s} P_L b)] (\bar{\tau} \tau) \\ &\quad -\frac{g_{\text{NP}}^2}{\Lambda^2} [C_P (\bar{s} P_R b) + C'_P (\bar{s} P_L b)] (\bar{\tau} \gamma_5 \tau). \end{aligned} \quad (7)$$

In the above expressions, g_{NP} and Λ are the NP coupling constant and mass scale, respectively. The C_i, C'_i ($i =$

V, A, S, P) are the unknown NP Wilson coefficients. Note that C_V and C'_V do not contribute to the decay $B_s \rightarrow \tau^+\tau^-$, but can contribute to the other $b \rightarrow s\tau^+\tau^-$ modes. The indirect bounds on these NP operators from $b \rightarrow s\gamma$ and $b \rightarrow s\ell^+\ell^-$ ($\ell = e, \mu$) were considered in [13] and found to be weaker than the direct bounds obtained from the ratio τ_{B_s}/τ_{B_d} .

In terms of all the Wilson coefficients, the branching ratio for this decay is given by

$$\mathcal{B}(B_s \rightarrow \tau^+\tau^-) = \frac{G_F^2 \alpha_{em}^2 m_{B_s}^5 f_{B_s}^2 \tau_{B_s}}{64\pi^3} \sqrt{1 - \frac{4m_\tau^2}{m_{B_s}^2}} \times \left\{ \left(1 - \frac{4m_\tau^2}{m_{B_s}^2}\right) \left| \xi \frac{C_S - C'_S}{m_b + m_s} \right|^2 + \left| \xi \frac{C_P - C'_P}{m_b + m_s} + \frac{2m_\tau}{m_{B_s}^2} [(V_{tb}V_{ts}^*)C_{10} + \xi(C_A - C'_A)] \right|^2 \right\}, \quad (8)$$

where $\xi \equiv (g_{NP}^2/\Lambda^2)(\sqrt{2}/4G_F)(4\pi/\alpha_{em})$. We now examine the decays $B_d \rightarrow K\tau^+\tau^-$, $B_d \rightarrow K^*\tau^+\tau^-$ and $B_d \rightarrow X_s\tau^+\tau^-$ in the presence of NP operators. The theoretical expressions are taken from [23, 24], with the replacement of m_μ with m_τ . We first consider one NP coupling at a time. We fix the value of the coupling by requiring that $\mathcal{B}(B_s \rightarrow \tau^+\tau^-) \sim 3.5\%$.

Note that when a single NP operator is present that enhances $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ to percent levels, since the SM contribution is negligible, the branching ratio would depend only on the magnitude of the NP coupling and not on its phase. The relevant branching ratios obtained by using the values for the NP couplings that yield $\mathcal{B}(B_s \rightarrow \tau^+\tau^-) = 3.5\%$ are shown in Table I.

Model	$B_d \rightarrow K\tau^+\tau^-$	$B_d \rightarrow K^*\tau^+\tau^-$	$B_d \rightarrow X_s\tau^+\tau^-$
SM	0.96×10^{-7}	1.15×10^{-7}	3.6×10^{-7}
C_A	0.35 %	0.19 %	0.80 %
C'_A	0.35 %	0.19 %	0.80 %
C_S	0.04 %	0.01 %	0.05 %
C'_S	0.04 %	0.01 %	0.05 %
C_P	0.12 %	0.03 %	0.15 %
C'_P	0.12 %	0.03 %	0.15 %

TABLE I. Branching ratios of $B_d \rightarrow K\tau^+\tau^-$, $B_d \rightarrow K^*\tau^+\tau^-$ and $B_d \rightarrow X_s\tau^+\tau^-$, when $\mathcal{B}(B_s \rightarrow \tau^+\tau^-) = 3.5\%$ and only one type of NP coupling is present. A kinematic cut $q^2 \geq 14.23 \text{ GeV}^2$ has been imposed in our theoretical calculations for the exclusive modes. We have set $g_{NP} = g_{EW} = 0.65$ and $\Lambda = 1 \text{ TeV}$. The theoretical errors on the branching ratios may be taken to be $\sim 25\%$.

From Table I we see that if there is only a single NP operator, the branching ratio of all these decay modes is less than 0.8%, and if the NP operator is scalar or pseudoscalar, it is even less than 0.2%. Therefore, the effect on the lifetime ratio τ_{B_s}/τ_{B_d} will be small. In any case, the increase in B_d decay rate tends to increase this

ratio and, hence, bring it closer to its central value of 1.002. It is also clear that the current 90% upper bound on the BR of $B_d \rightarrow K\tau^+\tau^-$ is consistent with $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ as long as the single NP operator is not of the axial vector kind.

Now we shall consider the implications of the presence of more than one NP operator. This is of course a more realistic scenario, since in any specific NP model, more than one effective operator is generally produced. For example, if the NP is leptoquark [7, 10, 15], in general we expect both $(S \pm P)$ and $(V \pm A)$ operators to be generated. And if the NP is a flavor-dependent Z' [16], one obtains all the $(V \pm A)$ operators.

The decay $B_d \rightarrow K\tau^+\tau^-$ depends on the combinations $(C_A + C'_A)$, $(C_S + C'_S)$, and $(C_P + C'_P)$ [23, 24], while the $B_s \rightarrow \tau^+\tau^-$ decay depends on the combinations $(C_A - C'_A)$, $(C_S - C'_S)$, and $(C_P - C'_P)$. Therefore, it is always possible to enhance $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ without affecting $B_d \rightarrow K\tau^+\tau^-$ significantly. On the other hand, $B_d \rightarrow K^*\tau^+\tau^-$ depends on the same combination of NP operators as $B_s \rightarrow \tau^+\tau^-$, except through the F_1 term (see Eqs. (A.7) and (A.12) of [23]) that depends on $(C_A + C'_A)$, but always adds positively to the decay rate. Therefore, the increased branching ratio of $B_s \rightarrow \tau^+\tau^-$ is expected to also increase the branching ratio of $B_d \rightarrow K^*\tau^+\tau^-$. The branching ratio of $B_d \rightarrow X_s\tau^+\tau^-$ will also naturally increase. Therefore, the latter two decay modes will be directly useful to constrain $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ even when multiple NP operators are present.

Since NP of the kind $b \rightarrow s\tau^+\tau^-$ contributes to both B_s and B_d decays (through $B_s \rightarrow \tau^+\tau^-$ and $B_d \rightarrow X_s\tau^+\tau^-$, respectively), the lifetime ratio τ_{B_s}/τ_{B_d} can be consistent with the observation even if $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ and $\mathcal{B}(B_d \rightarrow X_s\tau^+\tau^-)$ are large, since their contributions to the decay widths tend to cancel each other. The bound on $\mathcal{B}(B_d \rightarrow K\tau^+\tau^-)$ also offers constraints, however, these are only marginal, due to the arguments given above. Note that the consistency with the bounds on $B_s \rightarrow \tau^+\tau^-$, $B_d \rightarrow X_s\tau^+\tau^-$, and $B_d \rightarrow K\tau^+\tau^-$ does not need fine-tuning. For example, for $|C_A - C'_A| = 3.8$ (which leads to $\mathcal{B}(B_s \rightarrow \tau^+\tau^-) = 15\%$), any set of values of $|C_A + C'_A|$ and $|C_V + C'_V|$ in the range $[0, 1.4]$ are allowed by the upper bound on $\mathcal{B}(B_d \rightarrow K\tau^+\tau^-)$. The value of $|C_V|$ and $|C'_V|$ may now be chosen to be ~ 3 in order to make $\mathcal{B}(B_d \rightarrow X_s\tau^+\tau^-) \sim 12\%$, so that the τ_{B_s}/τ_{B_d} constraint is satisfied. Note that further constraints on $\mathcal{B}(B_d \rightarrow X_s\tau^+\tau^-)$ would decrease the upper limit on $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ from $\sim 15\%$.

IV. LEPTOQUARK

Leptoquarks (LQ) are particles whose quantum numbers are such that they couple to both the quarks and the leptons of the SM. Vector leptoquarks are predicted in many NP models like models of grand unification based on $SU(5)$ [25] and $SO(10)$ [26, 27] while scalar lepto-

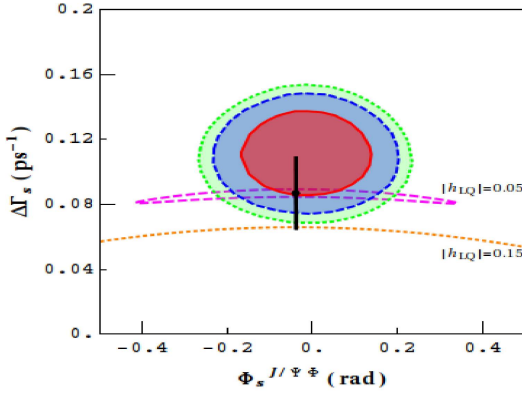


FIG. 2. The predictions of $(\phi_s^{J/\psi\phi}, \Delta\Gamma_s)$ within the scalar leptoquark model ($M_{LQ} = 250$ GeV), overlaid on the experimental constraints through $B_s \rightarrow J/\psi\phi$.

quarks can arise in models of supersymmetry with R-parity violation [28–31] and in extended technicolor models [32] where leptoquark states appear as bound states of technifermions. With the pre-LHCb data, a third-generation scalar leptoquark was shown to provide an explanation of the dimuon anomaly [20]. In this section we revisit the leptoquark explanation of the dimuon asymmetry in light of the recent LHCb data. We consider an SU(2) singlet scalar leptoquark \mathcal{S} with the Lagrangian,

$$\mathcal{L}_{LQ} \supset \lambda_{ij} (\overline{d^c})_j P_R \ell_i \mathcal{S} + \text{h.c.}, \quad (9)$$

where $(d^c)_j$ are the charge conjugate of the down-type quark fields, ℓ_i are the charged lepton fields and i, j are the generation indices. The field \mathcal{S} contributes to both M_{12}^{NP} and Γ_{12}^{NP} at one loop [13] and the contribution is proportional to the square of the effective coupling, $h_{LQ} = \lambda_{32}^* \lambda_{33}$.

A 95% C.L. lower bound of 210 GeV on the mass of a third-generation scalar leptoquark decaying to a $b\tau$ final state was reported in [33]. Here, we show our results for the leptoquark mass $M_{LQ} = 250$ GeV. It is worth mentioning that the above bound depends on specific assumptions and can be evaded if those assumptions are changed, however our conclusions do not change even if lower masses are considered.

In Fig. 2 we show the prediction of the leptoquark model for two values of $|h_{LQ}|$ in the $(\phi_s^{J/\psi\phi}, \Delta\Gamma_s)$ plane, superposed on the recent results from the LHCb [19]. The phase of h_{LQ} has been varied over. It is observed that a significant enhancement of $\Delta\Gamma_s$ above the SM prediction is not possible in this model.

A χ^2 fit in the $(\text{Arg}[h_{LQ}], |h_{LQ}|)$ parameter space, using the constraints on Δm_s [6] in addition to those on $\Delta\Gamma_s$ and $\phi_s^{J/\psi\phi}$ mentioned above, yields the maximum value of $|h_{LQ}|$ to be only around 0.05 (for $M_{LQ} = 250$ GeV at 95% C.L.). This gives $\mathcal{B}(B_s \rightarrow \tau^+\tau^-) \lesssim 0.3\%$. A leptoquark model, thus, cannot raise to $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ to the level of a percent. It is, therefore, also not enough to explain the dimuon anomaly. In fact, we have checked that if A_{SL}^b is included in the fit, then the $\chi^2 \geq \chi_{\text{SM}}^2 \approx 15$

even for very low values of leptoquark mass. This means that the LQ model cannot do better than the SM as far as the explanation of the dimuon anomaly is concerned.

V. FLAVOR CHANGING Z'

In this section we consider a flavor-changing Z' [16–18] gauge boson and examine whether it can offer an explanation of the dimuon anomaly while still being consistent with the recent LHCb data. We consider the Lagrangian density

$$\mathcal{L}_{Z'} \supset (R^{sb} [\bar{s} \gamma_\mu P_L b] Z'^\mu + \text{h.c.}) + R^{\tau\tau} [\bar{\tau} \gamma_\mu P_L \tau] Z'^\mu. \quad (10)$$

Note that Δm_s gets tree-level Z' contribution from $\mathcal{L}_{Z'}$ and is proportional to $(R^{sb})^2$. This restricts the value of R^{sb} to be very small. On the other hand, Γ_{12}^s is sensitive to the combination of couplings $\lambda = R^{sb} R^{\tau\tau}$, and we have already seen in Fig. 1 that a large value of Γ_{12}^{NP} is required for a solution of the dimuon anomaly. This means that a large value of λ will be needed in the Z' model. With a small R^{sb} , this could imply a very large value of $R^{\tau\tau}$, where the calculations would become nonperturbative and, hence, unreliable. The situation would become worse with increasing values of Z' mass. Therefore we have to stay away from the nonperturbative region.

Lower experimental bounds on the Z' mass can be a serious problem. Direct searches of pair production of $\tau^+\tau^-$ at the Tevatron have provided a lower bound on the Z' mass to be 399 GeV at 95% C.L. [34]. However since this bound assumes SM-like couplings of Z' to all quarks, it can be bypassed if the Z' is assumed to couple very weakly (or not at all) to the first-generation quarks. This allows us to consider a very light Z' , with mass as low as $M_{Z'} = 7$ GeV. Note that since $M_{Z'} \approx M_{B_s}$, the decay width of Z' can affect the results (at large couplings, the width may be as large as a few GeV) and has been taken into account in our calculations.

Note that, in principle, bounds on the effective coupling in $Z \rightarrow \tau^+\tau^-$ as obtained in [35] can put correlated constraints on $R^{\tau\tau}$ and $M_{Z'}$. However, the fit therein assumes a small imaginary part of the effective coupling, while the one-loop correction [36] to $Z \rightarrow \tau^+\tau^-$ through a Z' exchange has a large imaginary part for small $M_{Z'}$. The constraints in [35] are, therefore, not applicable in our case. A further analysis of $Z \rightarrow \tau^+\tau^-$, allowing for an imaginary contribution to the effective coupling, may yield stronger constraints.

In Fig. 3 we show the predictions of the Z' model in the $(\phi_s^{J/\psi\phi}, \Delta\Gamma_s)$ and $(\phi_s^{\text{SL}}, \Delta\Gamma_s)$ planes for some sample values of the couplings for illustration. (Note that $\phi_s^{J/\psi\phi} \neq \phi_s^{\text{SL}}$ [7, 37].) The figure shows that there are values of the couplings that can be consistent with the $J/\psi\phi$ data as well as the dimuon asymmetry data to within 2σ . The values of $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ in these allowed regions can be as high as $\sim 20\%$. However, constraints from the measurements of τ_{B_s}/τ_{B_d} , $\mathcal{B}(B_d \rightarrow X_s \tau^+\tau^-)$

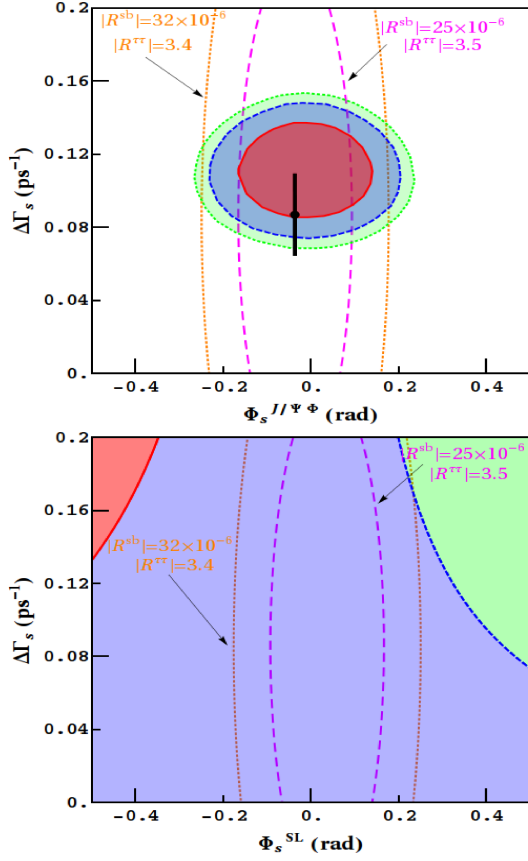


FIG. 3. The upper panel shows the predictions of the Z' model with sample values of the couplings in the $(\phi_s^{J/\psi\phi} - \Delta\Gamma_s)$ plane overlaid with the constraints from $B_s \rightarrow J/\psi\phi$. The lower panel shows the corresponding predictions in the $(\phi_s^{SL} - \Delta\Gamma_s)$ plane overlaid with the experimental constraints from A_{SL}^b and a_{SL}^d . We have used $M_{Z'} = 7$ GeV.

and $\mathcal{B}(B_d \rightarrow K\tau^+\tau^-)$ still continue to apply. In the case of a specific model such as this, the constraints would be more severe than those in Sec. III since the effective couplings (C'_V, C'_A) are now related to each other.

Figure 4 shows the result of a χ^2 fit in the $(|R^{sb}|, R^{\tau\tau})$ plane using all the experimental data: Δm_s , $\Delta\Gamma_s$, A_{SL}^b , seem consistent with all data to within 2σ , the results are reliable only when the couplings are perturbative, i.e. $\alpha_{R^{\tau\tau}} \equiv (R^{\tau\tau})^2/4\pi < 1$. We indicate this value of $R_{\tau\tau}$ by a horizontal line in the figure, and consider only the region below this line as the valid one. (The region below the line but very close to it may still have significant higher-order corrections.)

Even by demanding perturbative couplings in addition to $\chi^2 < 6.18$ (i.e. 2σ level), the branching ratio $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ can be as high as $\sim 20\%$. Thus, the Δm_s , $J/\psi\phi$, and A_{SL}^b data by itself cannot put strong constraints on the value of this branching ratio. The strongest constraints here come from τ_{B_s}/τ_{B_d} and $\mathcal{B}(B_d \rightarrow K\tau^+\tau^-)$. Taking into account these constraints, the value of $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ can be as high as 5%. This can happen, for example, with $R^{sb} = 15 \times 10^{-6}$, $R^{\tau\tau} = 3.0$, which makes $\mathcal{B}(B_d \rightarrow X_s\tau^+\tau^-) \approx 1.5\%$ and

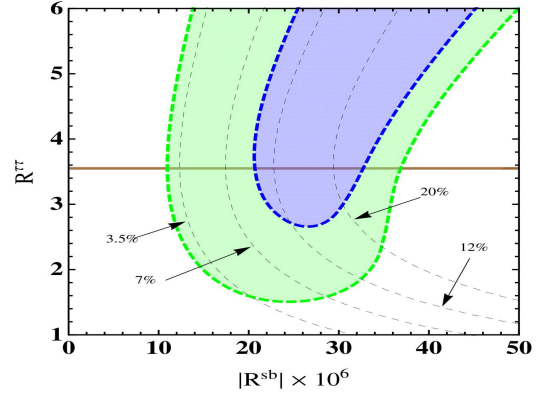


FIG. 4. Goodness-of-fit contours in the $(|R^{sb}| - R^{\tau\tau})$ plane for $M_{Z'} = 7$ GeV. The horizontal line corresponds to $R_{\tau\tau} = \sqrt{4\pi}$. Contours corresponding to $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ values of 3.5%, 7%, 12%, and 20% are also shown.

$\mathcal{B}(B_d \rightarrow K\tau^+\tau^-) \approx 0.35\%$, the former allowing a relaxation of the constraint from τ_{B_s}/τ_{B_d} .

Note that this value of $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ can alleviate the dimuon anomaly (from $\chi^2 = 15.1$ for the SM, to $\chi^2 = 9.5$); however, it is not enough to explain it. Some contribution from NP in the $B_d - \bar{B}_d$ mixing may also be needed, as was recently conjectured in [38].

VI. CONCLUDING REMARKS

We have investigated the possible enhancement of $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ that may help explain the observed anomalous like-sign dimuon asymmetry. Taking into account the constraints from the lifetime ratio of B_s and B_d , as well as the measurements of related $b \rightarrow s\tau^+\tau^-$ decay modes, we find that an enhancement up to $\mathcal{B}(B_s \rightarrow \tau^+\tau^-) \sim 15\%$ is allowed at 2σ . This bound may decrease with further constraints on $\mathcal{B}(B_d \rightarrow X_s\tau^+\tau^-)$.

Within the context of specific models, an enhancement of $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ to more than 0.3% is not possible with the leptoquark model, but the model with a light flavor-changing Z' that does not couple to light quarks can increase it to 5%. This helps alleviate the A_{SL}^b anomaly to some extent, but cannot account for it entirely, and contribution from NP in the B_d sector may be needed.

Our results with leptoquarks are similar to those in [13], however the updated LHCb data used by us has made the constraints on leptoquark parameters even stronger. On the other hand, the light Z' employed by us allows much larger values of the branching ratio than that predicted therein. Accounting for the dimuon anomaly to within 1σ , as indicated in [16], is not possible even with a light Z' , because of the new stronger LHCb constraints and the requirement of perturbative couplings.

If $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ is at the percent level, it will soon be within the reach of experiments, and could play an important role in our understanding of physics beyond the SM. The direct measurement of this branching ratio should, hence, be a high-priority.

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